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Abstract. In this paper we report new kinetic features of ions and electrons observed in the vicinity of the reconnection layer on 10 January 1997. This event has a three-dimensional magnetic field topological structure, which is much more complex than the previously suggested two-dimensional magnetic configuration. The ion distributions are non-gyrotropic and electrons show non-Maxwellian distribution functions. Acceleration of multiple ion beams, both parallel and perpendicular to the local magnetic field, have been observed. The perpendicular acceleration of the multiple ion beams can be explained by plasma mixing between the meandering ions accelerated around the ion diffusion region and the cold ions convected directly from the magnetosheath without passing through the X-line region. The parallel acceleration of the multiple ion beams can be understood by the fact that high-velocity ions ejected from the vicinity of the X-line mix with the plasma flowing directly across the boundary. We observed the kinetic effect of the separation of the electron and ion edges due to the time-of-flight effect. It is stressed that kinetic processes are the key to understanding these new observations that cannot be adequately explained by magnetohydrodynamic (MHD) models.

Key words. Space plasma physics (magnetic reconnection; charged particle motion and acceleration) – Magnetospheric physics (magnetopause, cusp, and boundary layers)

1 Introduction

The magnetic reconnection process is crucial to understanding fundamental plasma phenomena in geophysical/astrophysical plasmas, such as the Earth's magnetosphere, solar and stellar flares, and the astrophysical accretion disks. The rate of magnetic reconnection is controlled by the geometry of the dissipation region, where the ideal MHD description breaks down and the frozen-in condition is violated. Resistive MHD models typically produce slow reconnection, consistent with the theory of Sweet-Parker but inconsistent with the fast reconnection observed in nature. Understanding the mechanisms for breaking the frozen-in condition, the associated rate of reconnection and the deposition of magnetic energy into high-speed flows and energetic particles have been major issues. Recent intensive observations and particle simulations have provided us with some new clues for understanding collisionless reconnection (Drake, 2001; Birn et al., 2001; Shay et al., 2001; Pritchett, 2001; Hoshino et al., 2001; Hesse et al., 1999; Deng and Matsumoto, 2001; Oieroset et al., 2001; Nagai et al., 2001; Mozer et al., 2002; Scudder et al., 2002). A number of kinetic features observed by satellites are thought to play a significant role in magnetic reconnection. The observed velocity distributions are in general non-Maxwellian, such as those for high-speed ion beams. These beams are often observed when a satellite crosses the plasma sheet boundary (PSBL) (Parks et al., 1998; Lui et al., 1994; Frank et al., 1994; Eastman et al., 1984). Another class of observed non-Maxwellian distribution functions is for counter-streaming ions (CSIs) along the magnetic field line, often observed inside the plasmamoids/flux ropes (Mukai et al., 1996; Hoshino et al., 1997). However, detailed observations of particle distribution functions in the vicinity of the reconnection layer are still rare.

On 10 January 1997, a large magnetic cloud struck the Earth, resulting in a dramatic increase in auroral activity. During this period, GEOTAIL skimmed along the dayside magnetopause. Deng and Matsumoto (2001) found the first evidence of collisionless reconnection in the event. Naka-

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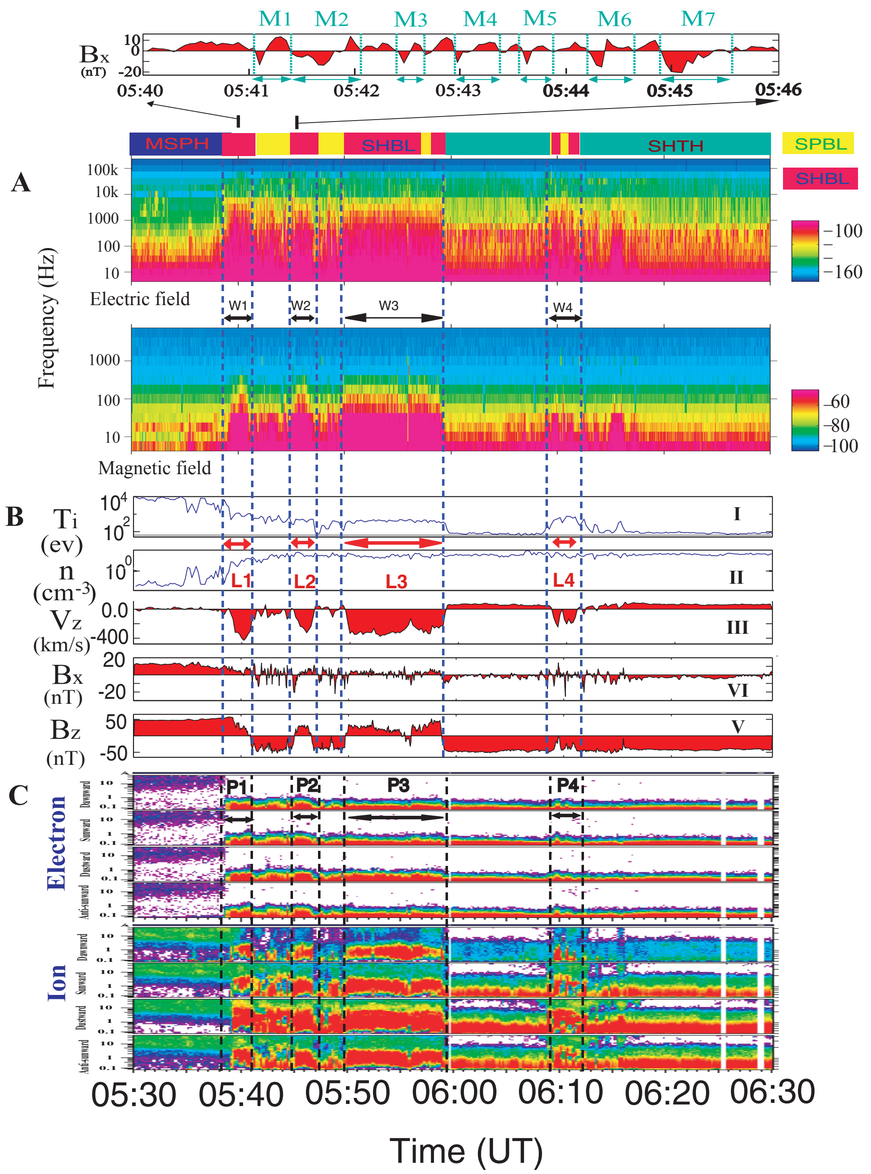

Fig. 1. GEOTAIL data from 05:30 UT to 06:30 UT on 10 January 1997, as the spacecraft traversed through the dayside magnetopause boundary. The GSM (geocentric solar magnetospheric) coordinate system is used with x toward the Sun, and the $x-z$ plane contains the Earth's dipole axis. Frequency-time spectrograms of the plasma wave electric and magnetic field data are shown in Part A. The bar above the electric field plots identifies the region encountered. The plot above that is an expanded time-scale plot of B_x magnetic field data. Part B contains plots of the plasma temperature, density, and z direction flow speed in panels "I", "II", and "III". The magnetic components B_x and B_z are shown in panels "IV" and "V". Part C contains the energy-time diagrams of electrons and ions with dawnward, sunward, duskward and anti-sunward directions, respectively.

mura et al. (1998) have shown the kinetic effect of the lower cut-offs in the ion distribution function due to the velocity filter effect. In this paper we report new dynamic features of ions and electrons observed in the vicinity of the reconnection layer in this event and the structure of the reconnection layer. Their implication to the ion dynamics associated with reconnection is also discussed.

2 Observations

The interesting Sun-Earth connection event was driven by a Coronal Mass Ejection (CME), which was first observed by SOHO 3 1/2 days earlier at 17:30 UT on 6 January 1997. This event is the first solar terrestrial disturbance followed from its solar source through to its consequences in the magnetosphere and ionosphere using the entire suite of resources of the International Solar Terrestrial Physics (ISTP) program.

Figure 1 gives the summary of the observations from the Plasma Wave Instrument (PWI) (Matsumoto et al., 1994), Low Energy Plasma (LEP) (Mukai et al., 1994) and Magnetic Field Experiment (MGF) (Kokubun et al., 1994) on GEOTAIL when it traversed the dayside magnetopause boundary during the period from 05:30 UT to 06:30 UT on 10 January. One prominent characteristic of the observations is the four high-speed plasma velocity spikes of V_z (L_1, L_2, L_3 and L_4) in panel "III" of part B, marked by the dashed lines and arrows. These highly-accelerated plasma velocity V_z spikes are a result of magnetic reconnection (Sonnerup et al., 1979). As GEOTAIL stayed in the southern magnetic hemisphere, the observed highly-accelerated plasma flow from reconnection was southward (negative value). Another striking feature is the observation of a series of bipolar signatures in the

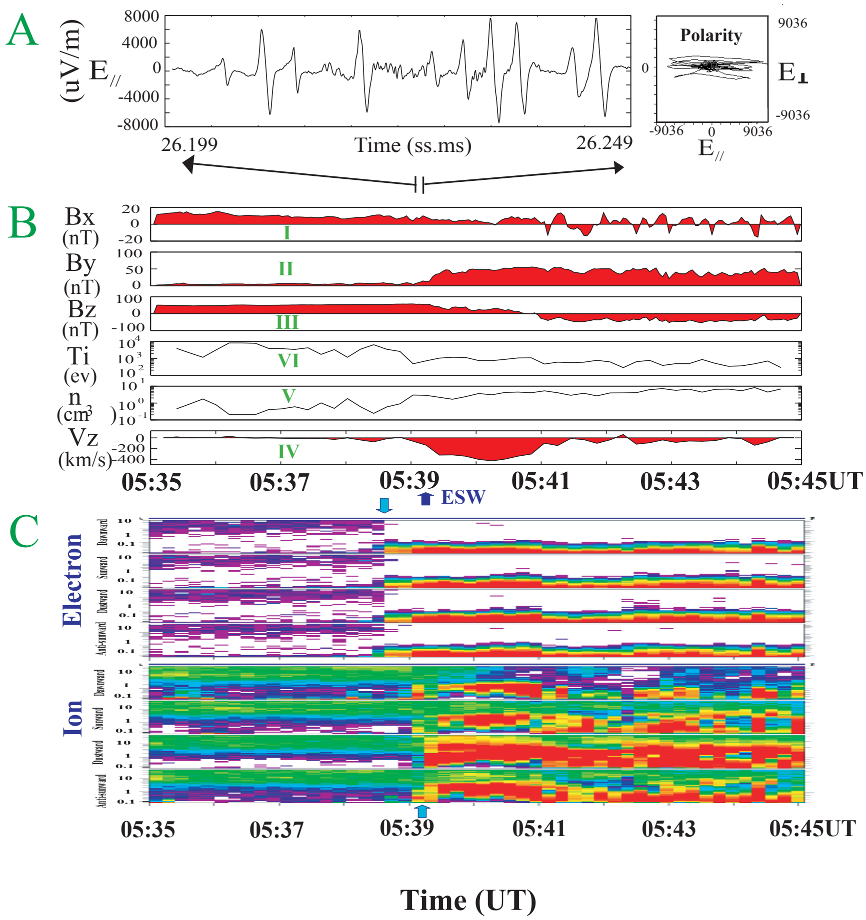

Fig. 2. Expanded time scale observations from 05:35 UT to 05:45 UT for the first acceleration flow event L_1 in Fig. 1. Part A is the plasma wave parallel electric field waveform in an expanded time scale showing ESWs. The plot of $E_\parallel$ verse $E_\perp$ is at the right side. The $E_\parallel$ and $E_\perp$ are the electric field components parallel and perpendicular to the ambient magnetic field B projected on to the antenna plane. In Part B, "I", "II", "III" are the magnetic field components B_x, B_y and B_z. The plasma temperature, density, velocity in the z direction are shown in panels "IV", "V", and "VI". Part C is the energy-time diagrams of electrons and ions with dawnward, sunward, duskward and anti-sunward directions, respectively.

magnetic field component of B_x, shown in panel "IV", which is the basic feature of the Flux Transfer Events (FTEs) (Russell and Elphic, 1979). At the top of Fig. 1 is B_x plotted in an expanded time scale using high-resolution magnetic field data. The observation of the series of B_x bipolar signatures (labeled M_1 to M_7) indicates that we believe that magnetic islands passed through GEOTAIL and reconnection was a transient and patchy process, not a steady one. For the bipolar signature of B_x, taking M_2 as an example, when a magnetic island resulting from magnetic reconnection passed through GEOTAIL, we observed a bipolar signature in B_x from negative (earthward) to positive (sunward).

It is interesting to see that all the accelerated velocity spikes are associated with the encounters of the Low-Latitude Boundary Layer (LLBL). The encounters of GEOTAIL with the magnetopause boundary are identified by the orientational change of B_z shown in the panel "V" of part B in Fig. 1 from northward (positive) in the magnetosphere to the southward (negative) in the magnetosheath or reverse. This crossing of the dayside magnetopause boundary (MP) from the magnetosphere to the magnetosheath is also confirmed by the plasma data, i.e. by the change in temperature in panel "I" and density in panel "II". The level of both plasma density and temperature intermediating between the magnetosheath (lower temperature and higher density) and magnetosphere (higher temperature and lower density) is one of the main characteristics of the LLBL. Due to the motions of magnetopause boundary, the first MP crossing was followed by three other incomplete ones before GEOTAIL finally exited into the magnetosheath (MS) at about 06:00 UT.

By carefully comparing panels "III", "IV" and "V" of part B in Fig. 1, we found that the B_x bipolar signatures and the highly-accelerated flow spikes of V_z appear at different regions of the reconnection layer. Looking at part B in Fig. 1 from left to right, as GEOTAIL went from the magnetosphere (MSPH) (positive B_z, higher temperature and lower density) into the magnetosheath (MSTH) (negative B_z, lower temperature and higher density), it encountered the MP several times due to the moving of the MP boundary. The first high velocity V_z spike of L_1 (panel "III") was observed around 05:40 UT near the magnetosphere boundary (SPBL) as indicated by positive B_z. No bipolar signatures of B_x were observed in panel "IV". GEOTAIL then recorded a series of large bipolar B_x signatures in the magnetosheath boundary (SHBL) during the period of 05:41 to 05:44 UT,where negative B_z but no high velocity flow of V_z was recorded. The second, high velocity flow V_z (L_2) was observed in the SPBL during the period of 05:45 to 05:47 UT without the bipolar B_x signatures. A series of bipolar B_x signatures were then recorded in the SHBL during the period of 05:47 to

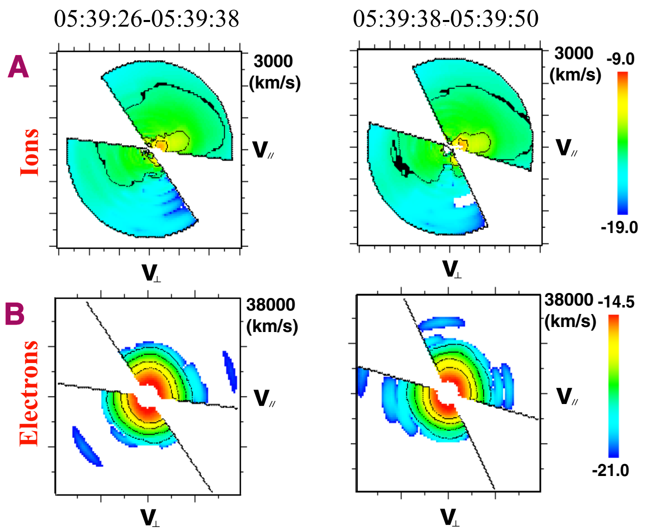

Plate 1. Distribution functions of ions (Panel A) and electrons (Panel B) for the case of the acceleration of multiple-beams perpendicular to the magnetic field. The distribution functions are the slices of the 3-dimensional distribution functions in the velocity plane including the magnetic field B ($V_{\|}$) and the $\boldsymbol{E} \times \boldsymbol{B}$ drift vector ($V_{\perp}$). The phase space densities are color-coded according to the color bar at the right-hand side.

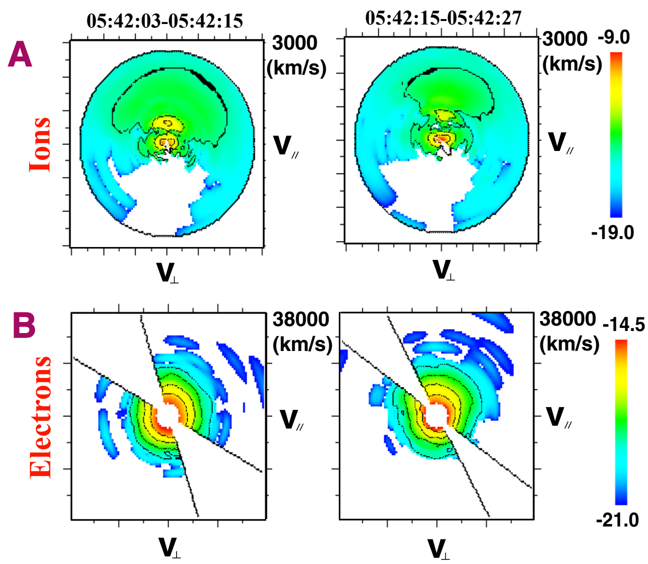

Plate 2. Distribution functions of ions (Panel A) and electrons (Panel B) for the case of the acceleration of multiple-beams parallel to the magnetic field. The distribution functions are the slices of the 3-dimensional distribution functions in the velocity plane including the magnetic field B ($V_{\|}$) and the $\boldsymbol{E} \times \boldsymbol{B}$ drift vector ($V_{\perp}$).

05:49 UT without the high velocity V_z flow. The tendency of the highly-accelerated V_z flow and the bipolar B_x signatures to appear in different regions of the reconnection layer is consistent with the simulation results of an asymmetric reconnection model at the dayside magnetopause, where the high speed flow appears on the magnetosphere side with positive B_z (Nakamura and Scholer, 2000).

In Fig. 1, Part A shows the dynamic frequency-time spectrograms of electric and magnetic fields from the high-time resolution Multi-Channel Analyzer (MCA), a part of PWI, during the period of 05:30 UT to 06:30 UT. Part C shows the electron and ion energy-time diagrams in the dawnward, sunward, duskward and anti-sunward directions, detected by LEP during the same period. We can see that coincident with the four velocity spikes (L_1, L_2, L_3 and L_4), there were correspondingly four bursts of wave activities (labeled W_1, W_2, W_3 and W_4), and four large increases in the fluxes of the energetic ions and electrons (labeled P_1, P_2, P_3 and P_4). The onset and cutoff of both the waves and particles happened almost simultaneously.

By checking Part C in Fig. 1 carefully, we observed the kinetic effects of the accelerated flow event. When GEOTAIL went from the magnetosphere side toward the magnetosheath side and encountered the LLBL at 05:39 UT, it first recorded the increase in the flux of the energetic electrons, and then the increase in the energetic ions. When GEOTAIL left the reconnection layer and finally exited into the magnetosheath side at 06:00 UT, it first left the ion edge and then the electron edge. Figure 2 shows the observations with expanded time scale for the period of 05:35 to 05:45 UT. We can clearly see the separation between the electron and ion edges (indicated by the arrows). Electron velocity distribution functions near the edge were highly structured at both low and high energies. These observations are quantitatively consistent with the quasi-stationary reconnection geometry (Gosling et al., 1990). It shows that the electron and ion edges of the LLBL are separated from one another, with the electron edge being located closer to the Earth. This offset in the electron and ion edges to the LLBL is a consequence of the fact that the entering magnetosheath electrons have much higher parallel speeds than the entering magnetosheath ions, while both the electrons and the ions share the same transverse drift.

A unique characteristic of this reconnection event is the existence of the strong B_y magnetic field component. Note that in panel “II” of part B in Fig. 2 there was a distinct increase in the B_y magnetic field component occurring almost simultaneously with the B_z magnetic field component decrease, as shown in panel “III” of part B when GEOTAIL approached the LLBL around 05:39 UT. The existence of the large and stable B_y component created three-dimensional magnetic field topology at the dayside magnetopause reconnection layer. The magnetic force lines in the magnetic islands are twisted and must have three-dimensional structure, not the two-dimensional configuration as previously assumed (Nakamura, et al., 1998). Without a large and stable B_y, the multiple X-line reconnection will only lead to the formation of isolated magnetic loops with two-dimensional structure, not the three-dimensional flux tubes with helical magnetic fields.

Though the Wave Form Capture (WFC) on GEOTAIL operates only 8.7 s every 5 min (Matsumoto et al., 1994), we do have the data from the WFC at critical periods when the 3-D transient magnetic reconnection took place near the spacecraft at the dayside magnetopause boundary layer. We observed a variety of waveforms in this reconnection event (Matsumoto et al., 2003). One of the interesting waveforms is for the Electrostatic Solitary Waves (ESWs), a series of large amplitude electric bipolar pulses parallel to the local magnetic field, which is shown at the top of Fig. 2.

The existence of the large and stable B_y magnetic field component is critical for the observation of ESW at the dayside magnetopause boundary for GEOTAIL. The ESW propagates along the ambient magnetic field, and GEOTAIL has only two sets of orthogonal electric field antennas extended in the ecliptic plane. Also, a simulation has shown that reconnection in the presence of a guide field is much more dynamic (Drake et al., 2003). The B_y guide field slows the convection of electrons away from the X-line, which enables the reconnection electric field to accelerate electrons in this region to a very high velocity. The resulting magnetic-field-aligned electron beams are Buneman unstable. The resulting turbulence evolves into distinct nonlinear structures consisting of localized regions of bipolar parallel electric field, corresponding to electron holes. The birth and death of these "electron holes" leads to strong electron scattering and associated energization (Drake et al., 2003).

An important property of the energetic population is its pronounced anisotropy. Plate 1 and Plate 2 show the velocity distributions of ions and electrons in the vicinity of the reconnection layer. The present observations reveal quite complicated ion and electron velocity distributions associated with reconnection. A striking point is the observation of the nongyrotropic ion distribution functions with multiple ion beams parallel and perpendicular to the local magnetic field.

Plate 1 is a slice of the three-dimensional distribution functions of ions and electrons in a plane including the magnetic field and the ion convection flow vector at the time around 05:39 UT. From panel "A" of Plate 1, it can be clearly seen that the ion distribution function is characterized by non-gyrotropic, bunched ions perpendicular to the magnetic field. The ion distribution consists of three well-ordered, cold dense, warm, and hot beams. The beams are roughly aligned in the plasma convection direction. Such a multi-beam structure has also been observed in the distant current sheet just after the passage of plasmoids (Tu et al., 1997). The electron distribution function acquired at the same time is shown in Panel B of Plate 1. The electron distribution functions have a flat-top distribution along the magnetic field line in the central part. By comparison with particle simulation and test particle simulation results (Hoshino et al., 1997), the kinetic behavior of the observed non-gyrotropic ion can be understood as due to the mixing process of the meandering ions. The energization of the meandering particle in the reconnection layer plays an important role in the formation of non-Maxwellian distribution functions (Speiser and Martin, 1996).

Plate 2 is a slice of the three-dimensional distribution function of ions and electrons in a plane including the magnetic field and the ion convection flow vector at the time around 05:42 UT. From panel "A" of Plate 2, it can be clearly seen that the ion distribution also consists of three well-ordered, cold dense, warm, and hot beams but parallel to the magnetic field. The electron distribution function acquired at the same time is shown in panel B of Plate 2. The electron distribution has a high-energy tail in the convection direction for the perpendicular acceleration case in Plate 1, while in the parallel acceleration case, the electron distribution has a high-energy tail in the direction of the magnetic field. The hybrid simulations of magnetic reconnection have shown that the ion distribution function can develop multiple beams as streams of ions penetrate one another (Shay et al., 1998; Krauss-Varban and Omidi, 1995; Nakabayashi and Machida, 1997). The multiple beam distributions become very prominent both close to the X-line and in the outflow region just downstream of the seperatrix. Under such circumstances a fluid treatment becomes problematic. Figure 3 shows the simulation result, in which two beams can be clearly seen in the distribution function of the ions from the downstream region displayed (Shay et al., 1998). The distribution of the fast species has a kidney bean-like shape with an axis of symmetry along the magnetic field, while the slow-moving ions appear as a Gaussian distribution. The electrons are accelerated to high velocities (exceeding the Alfvén velocity) first toward and then away from the X-line. Because the ions are much more massive, they cannot keep up with the electrons and separation between the two species occurs which produces electric fields that point toward the midplane in the inflow region and away from the X-line in the outflow region. In the dissipation region, it is this electric field, not the magnetic field, that accelerates the ions toward the X-line and then to Alfvén speeds away from the X-line. The observation of ESWs also supports the existence of the parallel electric field. The observation of the acceleration of multiple ion beams parallel to the magnetic field in Plate 2 can be understood by the fact that while some of the outward flowing ions just downstream of the discontinuity have been accelerated by the "shock",

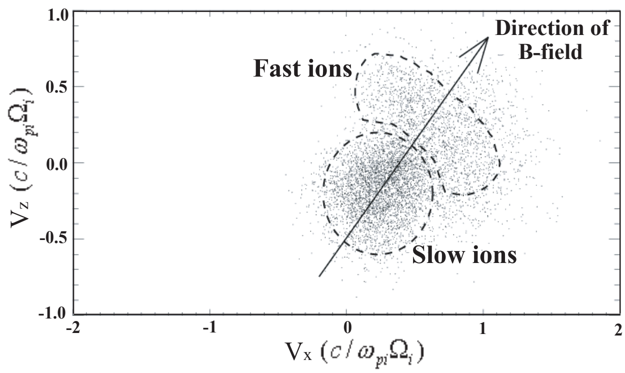

Fig. 3. Scatterplots of ion in-plane velocities. The ion beams come from separate locations, the slow one straddles the discontinuity and other, a fast one, is below the X-line from Shay (1998).

others have passed through the dissipation region where they were accelerated by large electric fields associated with the fast electrons. These two acceleration processes lead to two separate species of ions just downstream of the "shock": a background slow moving beam that has been accelerated by the discontinuity in the magnetic field across the "shock", and high-speed beam which has been accelerated by the large electric field near the X-line. The slow-flowing background ions come primarily from above the discontinuity and the fast beams are from the population near the X-line. The mixing of the two distinct species from different regions of space implies that the traditional MHD treatment of the slow shock is not valid.

It should be stressed that the acceleration of multiple ion beams parallel and perpendicular to the local magnetic field has been repeatedly observed during multiple crossings of the reconnection layer at the dayside magnetopause.

3 Conclusions and discussions

Magnetic reconnection plays a fundamental role in the dynamics of astrophysical plasma systems as the driver of explosive events, such as solar and stellar flares and more generally in dissipating magnetic energy as a balance to dynamo generation. Most of the observations about reconnection have been concerned mainly with the magnetic field and plasma signatures, and it is clearly shown that using only a velocity moment has lead to an incorrect conclusion. It is fundamentally important to examine the parent distribution functions from which the moment are derived (Parks et al., 2001; Chen et al., 2000). The wave and particle signatures will provide important information about the dynamics and small-scale structure of collisionless reconnection. It is clearly shown that kinetic processes are the keys to understanding the new observations that are not adequately explained by magnetohydrodynamics (MHD) models. What we have found is as follows:

1. It is revealed that the magnetic component B_x bipolar signatures and the highly-accelerated flow spikes of V_z appear in different regions of reconnection layer. The B_x bipolar signatures tend to appear on the magnetosheath side near the magnetopause boundary, while the highly-accelerated plasma flows are observed on the magnetosphere side. This tendency is consistent with the prediction of the asymmetric reconnection model at the dayside magnetopause.

2. We observed the separation of the electron and ion edges due to a time-flight effect. These observations are quantitatively consistent with the quasi-stationary reconnection geometry.

3. It is found that the ion distributions are non-gyrotropic and electrons show non-Maxwellian distribution functions. The dynamics of the ions are inherently nonfluid-like, with multiple ion beams both parallel and perpendicular to the magnetic field. The perpendicular acceleration of the multiple ion beams can be explained by the plasma mixing between the meandering ions accelerated around the ion diffusion region and the cold ions convected directly from the magnetosheath without passing through the X-line region. The parallel acceleration of the multiple ion beams can be understood by the fact that high-velocity ions ejected from the vicinity of the X-line mix with the plasma flowing directly across the "shock", which prevent the Rankine-Hugoniot conditions from being strictly satisfied.

4. We first observed ESWs associated with reconnection on the dayside magnetopause. This event has a three-dimensional magnetic field topological structure, which is much more complex than the previously suggested two-dimensional magnetic configuration. The existence of the large and stable B_y magnetic field component is critical for the observation of ESWs at the dayside magnetopause boundary for GEOTAIL. Simulations have shown that reconnection in the presence of a B_y guide field is much more dynamic. The guide field slows the convection of electrons away from the X-line, which enables the reconnection electric field to accelerate electrons in this region to very high velocity. The resulting magnetic-field-aligned electron beams are Buneman unstable. The resulting turbulence evolves into distinct nonlinear structures consisting of localized regions of bipolar parallel electric field, corresponding to electron holes. Such holes have been extensively studied in the auroral region of the ionosphere with FAST data. The observations of intense bipolar parallel electric fields at the magnetopause (Deng et al., 2000; Cattell et al., 2002), in combination with simulations, show strong evidence that these objects play a central role in dissipating magnetic energy during magnetic reconnection. These intense parallel electric fields scatter the electron beams, causing strong electron heating and a large effective resistivity. However, more observations and particle simulations are needed to understand the conditions under which these structures develop and their impact on electron energization and the rates of reconnection in magnetospheric and astrophysical systems. More work should be done about the fine structure in three-dimensions of the reconnection layer, especially the electron diffusion region, under different interplanetary conditions. There are still many key questions remaining. What is the observational criteria to identify the difference between single and multiple X-line reconnection? Where, when, and how does the reconnection take place? How is reconnection initiated? What is the nature of turbulence associated with reconnection? How does microturbulence couple to MHD or fluid turbulence? It is becoming increasingly clear that to understand these complex physics processes requires that both observers and modelers work hand-in-hand and not in isolation. This is an area in which the Cluster II

mission will play a very important role.

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